Novel Electrical Joints Using Deformation Machining Technology—Part II: Experimental Verification

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***Abstract*— This is the second part of the paper related to the exploration of deformation machining technology (DMT), originally developed at Bauman Moscow State Technical University, as it may apply to making electrical joints and comparing their performance to bolted and welded electrical joints. The DMT process is used to generate tooth-like profiles on two opposing surfaces that make the electrical joints which are later joined by applying a mechanical load. Part I contained a more detailed explanation of the DMT process and the description of the results of computer modeling of DMT joints in copper and aluminum. This paper provides the experimental results of the mechanical and electrical performance of copper and aluminum DMT joints which were compared to bolted and welded electrical joints of identical geometries. Measurements of tensile strength and electrical resistance, after thermal cycling and short-circuit testing, show equivalent or better performance of copper DMT joints compared with copper bolted and welded joints. In addition, it is observed that copper DMT joints have superior performance when compared with aluminum DMT joints, this was attributed to lesser gap filling and the springback effect that occurs after the mechanical load for making the joint is removed. The computer modeling results reported in Part I of this paper support these observations.**

***Index Terms*— Deformation machining, edge joint, electrical resistance, lap joint, short circuit testing, springback, thermal cycling.**

I. Introduction

ELECTRICAL joints for high-current applications, exceeding 100 A, are typically made using bolting, welding, or brazing. This paper reports the mechanical and electrical performance data on joints made using a novel joining technology called deformation machining technology (DMT) [1]–[3]. DMT is based on using a specially designed cutting tool [1], [4], [5] that undercuts and lifts (mechanically deforms) the machined surface to form a tooth-like structure as shown in Fig. 1.

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Computer modeling of copper and aluminum joints, as reported in Part I [6], showed that copper joints generate better joint contact manifested as a greater degree of gap filling, and better interlocking of the joined members than the aluminum joints as manifested by deformation angle and interference due to tooth upsetting. One of the difficulties identified in computer modeling of aluminum DMT joints is the springback after the joining force is removed, creating a gap between the adjacent DMT teeth. This paper compares the mechanical and electrical performance of DMT joints with that of bolted and welded joints. Successful implementation of copper DMT electrical joints for high-current carrying structures (exceeding 100 A) could possibly provide maintenance-free electrical enclosures by displacing bolted joints.

II. Optimal DMT Profile for Copper and Aluminum Joints

Based on the Part I computer modeling results [6], the optimal geometry elected for the evaluation of the mechanical and electrical performance was similar to M-Cu1 and M-Al2, with parameters as shown in Fig. 2 and Table I.

III. Experimental Setup and Results

Both lap and edge joints were subjected to a number of tests and evaluations and compared against standard bolted or welded joints.

Lap joint is defined as a joint between two plates, where the contact between the plates is made between the flat surfaces (width and length dimensions) of two plates. Edge joint is defined as a joint between two plates, where the contact between the plates is made on the short transverse surface (thickness and either width or length dimensions) of the two plates. Fig. 3 shows typical lap and edge joints.

A. Thermal and Electrical Cycling—Lap Joint

Two standard bolted and one DMT joints, shown in Fig. 4, were subjected to thermal and power cycling at 100-A current in the following stated order.

Cycle 1) *Thermal Cycling:* 1 h at 100 °C/3 h at 30 °C; total cycles = 24.

Cycle 2) *Power Cycling:* 2 h ON/1 h OFF for 5 d.

Cycle 3) *Power Cycling at Variable Ambient:* 2 h current ON/1 h current OFF and 1 h at 50 °C/3 h at −5 °C for 2 d.

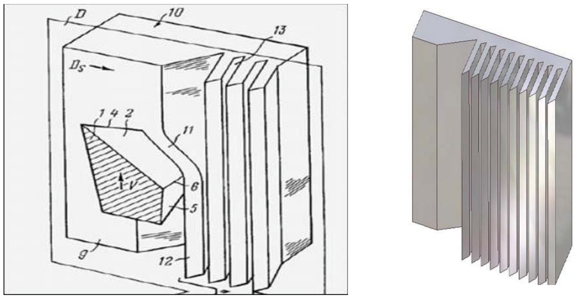


Fig. 1. Principle of DMT and a schematic of flat DMT surface.

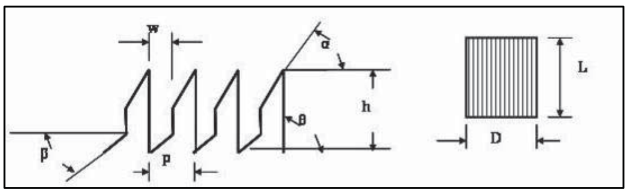


Fig. 2. Parameter nomenclature for DMT profile used in computer modeling.

TABLE I

OPTIMAL TOOTH PROFILE AND ASSEMBLY LOADS FOR MACHINED COPPER AND ALUMINUM PLATES

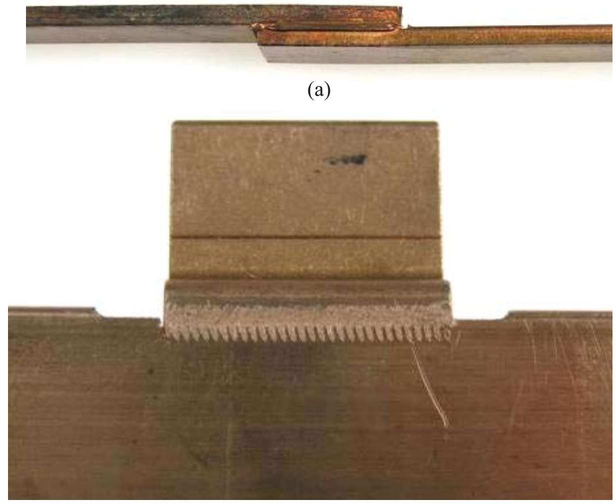
DMT parameter	Dimension	Units	Variation	
			M-Cu1	M-Al2
Joint length	L	mm	20	20
Joint width	D	mm	20	20
Pitch	p	mm	1.28	1.28
Groove width	w	mm	0.73	0.73
Fin height	h	mm	1.83	1.83
Fin angle	θ	degrees	90	90
Fin tip angle	α	degrees	45	45
Root angle	β	degrees	45	45
(Fin width)	(Ref)	mm	0.55	0.55
Assembly load	–	M-tons	17	10
Slenderness ratio	h/fin width	–	3.33	3.33

TABLE II

TENSILE RESULTS OF LAP JOINTS AFTER THERMAL CYCLING

Joint	Type	Assembly force (tons)	Pull force (kN)	Comment
Cu-Cu	Bolted	Not applicable	8.6	Standard joint
Cu-Cu	Machined	17 tons	9.8	Joint slippage
Cu-Cu	DMT	17 tons	10.86	Some joint slippage
Al-Al	Machined	10 tons	1.9	Joint sliding
Al-Al	DMT	10 tons	2.1	Joint slippage

Potential drop (measured in millivolts) was measured across each copper joint at a nominal 100-A current after each of the environmental cycles and resulting resistance was computed. All measurements were made at room temperature, while the samples may be "cold" or "hot" as a result of either thermal or electrical or both cycles. Fig. 5 shows the results with the overall conclusion that the copper DMT lap joints have a slightly better performance compared to bolted joints as indicated by the consistently lower joint resistance.



(a)

(b)

Fig. 3. Joints. (a) Lap joint. (b) Edge joint.

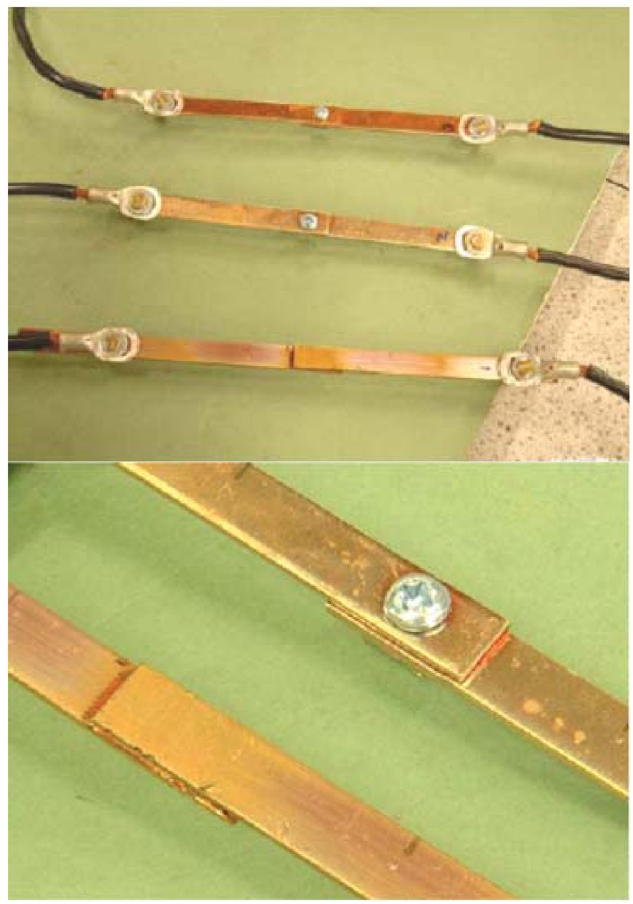


Fig. 4. Test samples of standard bolted joints and DMT joints used for testing.

B. Short Circuit Test—Lap Joint

Copper DMT and bolted lap joints were subjected to a short-circuit test of 12 kA for 0.1 s. Both bars bent under magnetic force and there was no separation or joint slippage in the DMT joint as seen in Fig. 6. In addition, the electric resistance of the DMT joint was unchanged after the SC test.

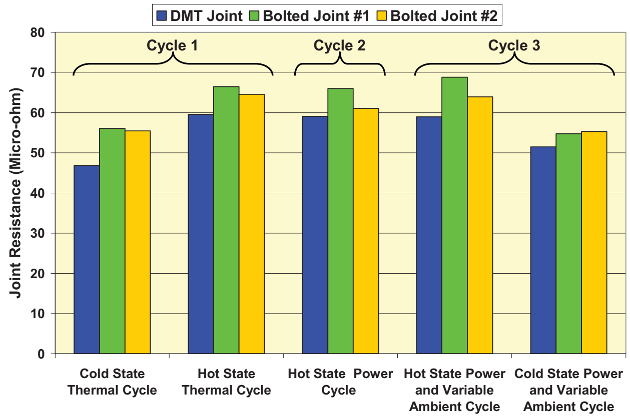


Fig. 5. Results of thermal and power cycling on copper joint electrical resistance.

Fig. 6. Lap and bolted lap joints after short-circuit test.

C. Tensile Strength—Lap Joint

The lap joint, as shown at the right of Fig. 6, was tested in both the machined and DMT condition against standard bolted lap joint. The pull testing was done after the samples were subjected to thermal cycling, Cycle 1, above. Table II shows the results of the tensile tests.

These results show that the copper DMT joints have comparable tensile strength to bolted joints. Thermal cycling generates complex stresses seemingly loosening the aluminum machined DMT joint to the point of a very low strength. In light of that condition, DMT aluminum joints were not tested. Exclusion of aluminum joints from testing is also justified in the literature [7], [8].

IV. Powered Testing of Edge Joints

Two sizes of edge joints were tested:

1) copper joint of 6-mm wide by 27-mm long at 400 A;
2) copper joint of 6.35-mm wide by 38.1-mm long at 200 and 300 A;
3) aluminum joint of 6.35-mm wide by 38.1-mm long at 200 and 300 A.

The 6-mm-wide by 27-mm-long joint was tested in "as manufactured" condition at 400 A, and the maximum temperature rise was recorded once the joint temperature stabilized to within ±0.1 °C and the test data are shown in Table III.

TABLE III
Test Results on 6-mm-Wide by 27-mm-Long Joints at 400 A

Joint type	Temeperature rise (°C)	Maximum joint temperature (°C)
Copper DMT	17.0	39.6
Copper-standard welded	18.4	41.0

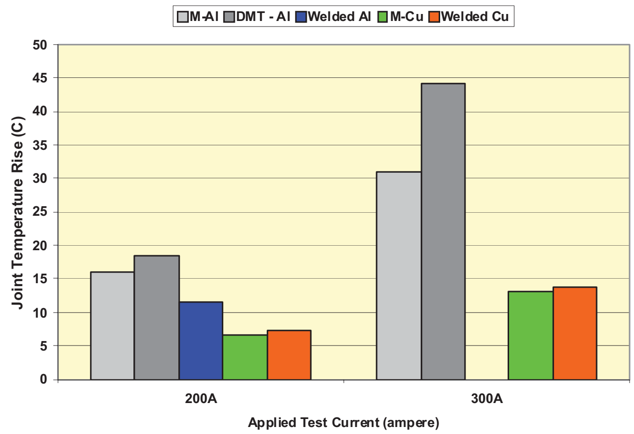


Fig. 7. Temperature rise for edge joints of 6.35 mm × 38.1 mm.

It is clear that the DMT joint is comparable if not better than the welded joint.

Edge samples of 6.35-mm wide by 38.1-mm long in copper and aluminum were tested at 200 and 300 A. The procedure for testing at 200 A required that the joint came to equilibrium for at least 1 h with a maximum temperature variation of ±1 °C before the joint temperature rise was measured. After that test, the current was changed to 300 A, and under that condition, the aluminum DMT joint never thermally stabilized. The results are shown in Fig. 7. Clearly again, the Cu-machined and Cu-welded joints show similar performance. However, both the machined aluminum and the DMT aluminum joints showed higher temperature rise at the joint compared to the welded aluminum joint, at least at 200 A. At 300 A, both machined and DMT joints showed a significant rise in joint temperature which clearly indicates that these joints are not acceptable as a replacement to aluminum-welded joints.

V. Conclusion

1) Copper DMT joints showed sufficient mechanical strength when compared to bolted joints and have an equivalent electrical performance to either bolted or welded joints.
2) Copper DMT joints appeared attractive for electrical joints provided that the DMT tooth characteristics could be accommodated by the joint design, particularly for edge joints.
3) As predicted during computer modeling, aluminum DMT joints showed inferior performance compared to copper DMT joints, which is believed to be due to the springback of the deformed teeth and the potential loosening during thermal cycling.
4) Aluminum DMT lap joints showed inferior performance compared to bolted and welded aluminum joints.

5) At 300-A power test of edge joint, the aluminum DMT joint never thermally stabilized, which was another indication of inferior performance when compared to copper DMT joints.
6) Tensile characteristics of DMT joints were directional and require appropriate design if that strength characteristic is required.

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